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Aging and Visual Function of Military Pilots: A Review

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This report reviews what is known about the effects of age on visual function and discusses the implications of age-related changes in vision for the flying performance of military pilots. Most visual functions decline to some degree with age, and the rate of decline has been roughly characterized in the general population. There is, however, virtually no data on military pilots, and extrapolation from the general population requires caution. Individual variation in the effects of age is great, and military pilots are a select group presumably in better general health than the general population. Several visual functions that decline with age seem particularly relevant to pilot performance: contrast sensitivity, dynamic acuity, recovery from glare, function under low illumination, and information processing. Vision examinations currently given to military and commercial pilots do not measure these visual functions. The feasibility of supplementing existing vision examinations with measurements of these functions should be explored; such an assessment should consider both research issues and policy implications. Research is needed on several major problems in this area. It is not possible at present to characterize well the effect of changes in visual function on the performance of complex tasks, such as flying. This report suggests several specific measures that might help characterize the effects of changes in visual function on pilot performance. Data on changes in visual functions with age should be collected from military pilots, preferably with multivariate, longitudinally designed studies. Research is suggested to assess the extent to which experienced pilots may compensate for declining visual functions and to determine how such compensation is achieved. The report suggests studies of the interaction of age with other factors, such as cardiovascular changes, that may affect performance, especially under stress.

IN 1979, THE COMMITTEE on Vision received a request from the Department of the Navy to evaluate the current state of knowledge about the ways in which age affects visual function, emphasizing the implications for the flight performance of older military pilots, particularly those in the Navy. In response to this request, the committee created Working Group 55, which reviewed the existing scientific literature on the topic. The working group found that most of the literature concerns basic visual and perceptual functions measured under laboratory conditions, using subjects from the general population. Research on the effects of age on complex task performance involving vision has been limited, and studies specifically concerning flying performance are almost nonexistent.

In conjunction with this study, the committee organized a symposium on aging and human visual function. Papers prepared for the symposium give extensive reviews of the effects of age on different functions and provide access to the general literature. A full report of the symposium is being prepared for publication (69).

The working group encountered a major obstacle early in its deliberations: existing knowledge does not allow the specification of those visual functions that are most crucial to flying performance. It is therefore difficult to know whether deterioration in some function actually affects performance, despite research efforts and eval-

The project that is the subject of this Working Group 55 report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competencies and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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uation studies by several groups, including the Committee on Vision (57). Previous evaluations do agree that particular visual functions play an important role in flying performance, even though we cannot quantify how performance would be affected by the deterioration of those functions. The working group has drawn on these earlier evaluations in selecting visual functions for study; the choice, however, is necessarily subjective, and the functions considered in this study do not constitute an exhaustive list.

The working group also attempted to evaluate the relevance of the general literature to the problems of military aviation. This report discusses a number of methodological problems, including the difficulty of extrapolating findings obtained with a general population of subjects to military pilots. The working group points out that, even though a fair amount is known about how laboratory measures of visual function change with age, very little can be said with certainty about how these changes affect the field performance of pilots.

Although the effects of age on pilot performance concern both military and civilian agencies,[1] this report does not discuss issues of policy, since they are outside the charge to the working group. However, as a caveat to those concerned with the implications of the effects of age on flying performance, the working group consistently emphasizes the limitations of the data it reviewed.

VISUAL TASKS OF NAVY PILOTS[2]

The visual tasks of military pilots are often far more demanding than those of commercial pilots. The working group discussed these tasks, particularly those of Navy pilots, but did not attempt to characterize visual performance demands extensively.

Navy pilots perform several general types of missions. These may be grouped as fighter/attack, maritime patrol/antisubmarine warfare/electronic countermeasures, rotary wing (helicopter), transport, and training. In some missions, pilots face particularly demanding visual tasks. One of the most difficult challenges is landing aboard an aircraft carrier, particularly in rough seas or at night. A pilot approaching an aircraft carrier must adjust the glide slope path according to signals from an orange visual indicator (the meatball), whose vertical position indicates necessary glide slope corrections. The margin for error is small and the task requires diligent practice. The earlier a pilot identifies the meatball while approaching the carrier, the greater is the opportunity to adjust the glide path in order to avoid either a "wave off" by the landing signal officer or a "bolter." A bolter is a carrier landing in which the plane is not caught by any of the arresting cables on the deck and thus is forced to take off again, i.e. a touch-and-go landing.

Several other aspects of military aviation pose especially demanding visual tasks (64,83). For example, in combat maneuvers, pilots must accurately estimate the range and altitude of objects and the direction of movement and maneuvers of other aircraft. Visual demands are also great in formation flying, midair refueling, and target acquisition and object identification, both air-to-air and air-to-ground. Several conditions place special constraints on the visual tasks of military pilots: the high G forces in sustained acceleration during combat maneuvers, drastic changes in ambient light levels during rapid climbing and diving or in night missions, and the restraints of protective clothing, helmets, and oxygen masks. The pilot must shift attention back and forth between the outside environment and the cockpit (even with the assistance of heads-up displays).

Other visual demands are more similar to those encountered in commercial aviation, such as routine takeoffs and landings, visual navigation, and avoidance of collision. The pilot's apportionment of attention and perceptual workload are of special concern in both military and commercial aviation. Modern pilots cannot be evaluated simply in terms of their physical skills; they must also be considered as managers of complex information systems.

AGING AND VISUAL PERFORMANCE

This section discusses the visual functions that the working group feels are most crucial to performance of a pilot's tasks. We sketch briefly what is known about the effects of age on these functions. For more detail, the reader may refer to the literature cited; more thorough reviews and discussions of research concerning age effects on these and other visual functions can be found in Sekuler and coworkers (69). Almost all data discussed below were obtained on subjects from the general population; virtually no data based on military pilots were found. The likely relevance of age to flying performance is commented on, but only in the most general terms; existing knowledge is, in general, not sufficient to evaluate precisely how these age-related changes affect performance.

Light Transmission

The optical elements responsible for the transmission

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[1]The Navy recently rescinded its policy of automatically shifting aviators from Service Group I to Service Group III at age 45, a shift that removed them from pilot-in-command status. Service Group I aviators are considered medically qualified for any type of flying; Service Group III aviators may not fly single-seat aircraft and may pilot dual-control aircraft only when accompanied by a Service Group I aviator.

The Institute of Medicine examined the general effects of age on the performance of commercial airline pilots. This study (35) pertains to the Federal Aviation Administration's rule that commercial pilots are automatically retired at age 60.

[2]This brief sketch of Naval aviators' visual tasks is intended for readers unfamiliar with this topic.

and refraction of light show change at an earlier age (35-45 years) than do the retina and higher neural mechanisms of the visual system, which manifest change at 55-65 years of age (22). Changes in the pupil and the lens are the most prominent (80).

The Pupil—Advancing age brings a reduction in the pupil's resting diameter under both dark- and light-adapted conditions (6). This reduction in pupil size is termed "senile miosis." As a result of senile miosis and changes in the media, retinal illuminance diminishes with age; this presumably occurs to a similar degree in older Navy pilots, placing them at a disadvantage when operating under low illumination levels. Age differences in the latency of the pupillary reflex appear to be small and unlikely to be of much practical significance (80).

The Lens—The crystalline lens becomes harder (sclerotic) and more yellow with age. With this hardening, the aging lens gradually loses its ability to bring near objects into focus (presbyopia). Loss of accommodative amplitude is one of the most universal changes in visual function with age. Using three simple equations, Hofstetter (32) summarized data from several investigators and several thousand eyes.[3]

For example, the average 40-year-old should have 6.5 diopters of accommodative amplitude and, properly corrected for distance viewing, will find targets blurred if they are closer than 15 cm from the spectacle plane. At the same age, corresponding values bracketing 95% of the population are 5.0 diopters (blurring at 20 cm) and 9.0 diopters (blurring at 11 cm).

Pilots also show an age-related loss in accommodative amplitude. Szafran (76) reported a correlation in pilots between age and amplitude of accommodation of −0.75. He concluded that the degree of accommodative loss experienced by his pilot subjects was comparable to that reported for nonpilot samples.

More important, older Navy pilots report that they, too, find it increasingly difficult to bring near objects into focus. However, their medical records have not been analyzed in a way that gives a clear idea of the rate of progression of presbyopia in these individuals, who are presumably in better health and more physically fit than the general population.

Yellowing of the lens decreases its transmission of short wavelength light, impairing the ability of older people to discriminate between different colors within this part of the spectrum (65). This impairment appears to occur in all older people, presumably including Navy pilots.

Age-related changes in the lens also make older observers more susceptible to glare (59); age-related changes in the vitreous humor have a similar effect (3). This increased susceptibility to glare would make the visual tasks of pilots more difficult under some daytime and nighttime flying conditions.

Dark Adaptation

Two different aspects of dark adaptation must be considered: first, the asymptotic level of sensitivity to light and, second, the rate at which that level is approached. It is well established that, at all stages of dark adaptation, observers over age 40 are less sensitive to light than are younger observers (5,53). Consequently, the final level of sensitivity reached by the old is well below that reached by young observers.

Among pilots in the Lovelace study (75), the expected correlation between age and level of dark adaptation was also observed. However, older pilots appeared to have somewhat greater sensitivity to light under scotopic conditions when tested with the same instrument earlier with subjects from the general population (20). There are several impediments to a straightforward interpretation of this result. First, Szafran (75) did not test the appropriate controls himself, relying on measurements made more than a decade earlier by others. Second, the psychophysical methodology does not rule out the possibility that apparent differences in sensitivity between pilots and other subjects are the result of differences in criteria, rather than in physiological sensitivity.

There is some controversy over changes in the rate of dark adaptation with age. Birren and Shock (5) found no change in the rate of adaptation with age, but Domey and coworkers (19) concluded that both rod and cone adaptation slowed with age.

Several factors have been postulated to explain age differences in dark adaptation. These include age differences in retinal metabolism and the altered spectral content and decreased amount of light reaching the retina. Senile miosis and increasing opacity and yellowing of the lens decrease retinal illuminance and change the refractive index of the eye for certain wavelengths.

Weale (79) has estimated that, as a result of changes in the ocular media associated with aging, the average 60-year-old retina receives only one-third as much light

[3]The mean amplitude of accommodation expected for observers 60 years of age or younger can be estimated as: amplitude = 18.5 − 0.3(age). Defining the limits of "normal" by 2 S.D., the maximum expected amplitude of accommodation is given by: amplitude = 25 − 0.4(age). The minimum amplitude to be expected is: amplitude = 15 − 0.25(age). The estimates assume that amplitude of accommodation is measured by the "push up" method (observer is corrected for distance and maximum accommodative amplitude measured by subjective blurring as a target is brought closer to the observer). Amplitude is given in diopters and the spectacle plane, 14 mm anterior to the corneal apex, is taken as zero distance.

as its 20-year-old counterpart under comparable conditions of illumination. Sensitivity, then, may appear to decrease with age simply because less stimulus energy reaches the retina (80). But the limited amount of available data makes it difficult to rule out the possibility that nonoptical changes also play some role (60).

Acuity

The ability to see fine detail in stationary targets declines somewhat in adulthood to about age 55-60, and more markedly thereafter in the general population (60). The age-related loss in static acuity is exaggerated under conditions of low illumination. Although increases in low levels of retinal illuminance improve acuity for both young and old adults, at high illumination levels visibility may be reduced among older observers because of increased sensitivity to glare. The causes of age-related static acuity loss, in order of decreasing frequency, are: refractive error, cataract, senile macular degeneration, retinal pathology (including diabetic retinopathy), and open-angle glaucoma (60). The periodic ophthalmological examination required of naval aviators appears likely to detect the pathological conditions most likely to affect visual acuity. Since aviators with significant pathology are screened out by the examination, they need not concern us here.

Contrast Sensitivity

Recently, the contrast sensitivity function (CSF) has emerged as a potentially important method for characterizing visual status. This method yields information that cannot be duplicated by other, more traditional, procedures. Rather than discuss the method or its theoretical implications, we merely summarize the current state of work on contrast sensitivity and aging. For readers not familiar with this method, the appendix to this report provides some useful background.

The CSF summarizes the visual system's overall sensitivity to targets of varying spatial structure, from the finest structures that can be resolved to the coarsest. The CSF itself depicts sensitivity, the reciprocal of threshold contrast, as a function of spatial frequency.

Several studies have examined contrast sensitivity at different ages. Although Arden and Jacobson (1) reported no influence of age on contrast sensitivity, Skalka (72) and McGrath and Morrison (54) reported that contrast sensitivity at all spatial frequencies declined with age. Arundale (2) and Derefeldt and coworkers (18) showed that losses of contrast sensitivity were confined to spatial frequencies above 4 cycles/degree. Sekuler and coworkers (68) found that, among older observers who had been screened for good acuity, losses were confined to spatial frequencies below 4 cycles/degree. At present, it is difficult to know the role of various factors in generating this diverse set of outcomes: observer selection, methodology, ocular pathology, etc. As yet, then, the results lend themselves only to the generalization that there are changes in contrast sensitivity with age and that these changes may not be related in any simple way to changes in acuity.

Changes in contrast sensitivity are likely to influence an individual's ability to perform certain visual tasks. This is of some concern because conventional clinical tests of Snellen acuity do not necessarily reflect individual differences in contrast sensitivity at low or intermediate frequencies. Research efforts are currently exploring the relationship between CSF and performance of complex real-world visual tasks, such as flying airplanes. One recent study demonstrated a strong correlation ($r = +0.80$) between the contrast sensitivity of jet pilots and the distance at which they could detect ground targets in an aircraft simulator (25).

Dynamic Visual Acuity

There is general agreement that acuity for a moving target decreases as a function of the target's angular velocity relative to the observer. This result is obtained when the target moves past the observer in a horizontal direction (51), a vertical direction (56), or in a circular path on a plane tangent to the line of sight (50). Similar results are obtained when a stationary target is viewed from a rotating platform (56) or from an airplane in flight (27).

The relevance of dynamic visual acuity (DVA) to flying is apparent for tasks requiring the recognition of targets moving at angular velocities similar to those tested. The integrity and coordination of visual and oculomotor functions needed for good DVA performance would appear to be important to a large class of tasks requiring rapid scanning and acquisition of visual targets. DeKlerk and coworkers (17) reported that in-flight criterion measures of instrument, formation, and night flying performance were more closely related to DVA than to static acuity. To the extent that visual requirements in automobile driving are similar to those in piloting an airplane, the work of Burg and his collaborators should also be considered. Burg (9,10) concluded that, among the seven vision tests in his battery, DVA showed the strongest and most consistent relationship to automotive driving record. Henderson and Burg (31) found a significant correlation between DVA and frequency of accidents of bus and truck drivers.

There are few data on which to base a discussion of the effects of age on DVA. Experiments by Burg (8) and Reading (62) indicate that progressive decline in acuity with advancing age is amplified by increasing target velocities. Reading argues that the degradation in DVA with age is more likely the result of changes in the dioptric characteristics of the eye than of changes in ocular tracking ability. However, Goodson and Morrison (28) have demonstrated that poor DVA performance by an older subject can be improved dramatically with training.

Oculomotor Behavior

Except for clinical observations, not much is known about the oculomotor system as it ages. Here we consider two of the better-established changes that may affect flight-related performance: pursuit eye movements and fixation stability.

Pursuit Eye Movements—Sharpe and Sylvester (70) measured pursuit eye movements in young observers ranging in age from 19-32, and in older observers ranging in age from 65-77. Even at a quite slow target speed, the older subjects showed a decreased gain. Gain is the ratio of the magnitude of a system's response and the magnitude of the input evoking that response. This diminished gain would result in greater movement of the retinal image of any pursued target. In turn, this increased retinal image movement might contribute to losses in dynamic visual acuity with age (see above). Since Sharpe and Sylvester made measurements with only two age groups, it is difficult to relate their results to known changes in DVA with age.

Fixation Stability: Stable and accurate fixation is a prerequisite for many visual functions. However, not much is known definitively about the connection between fixation stability and age of the observer. Anecdotal reports suggest that older observers who are free of ocular and neurological pathology have stable fixation. Precise, quantitative comparisons with younger observers, however, are lacking. We do wish to call attention to the report by Dannheim and Drance (15) of fixation instabilities in older observers. Dannheim and Drance studied spatial summation at various eccentricities (maximum = 30 degrees) in observers ranging in age from 20-79 (total $n = 35$; greater than 60 years of age, $n = 11$). They could not make measurements under scotopic conditions because of difficulties in fixation, particularly in older subjects. Measuring adaptation functions against a completely dark background, to determine the absolute level of rod adaptation, might particularly challenge the fixation ability of older observers. Difficulties in maintaining fixation might play some role in older persons' apparently reduced sensitivity in some dark-adaptation experiments. Moreover, fixation instability would particularly impair the detection of small targets. It is important to note that this possibility is frankly speculative. We have no data from pilots to show how their fixation stability might change with age.

The Visual Field

Visual fields are usually assessed with either static or kinetic perimetry. Although other forms of perimetry are possible (36), virtually all that is known about visual fields in aging humans comes from tests of the detectability of incremental targets against some background.

Studies of changes in the visual field with age provide two kinds of related information: (1) kinetic perimetry describes changes in the boundaries of the visual field and (2) static perimetry describes changes in sensitivity across the visual field. Most work using kinetic perimetry indicates that the visual field constricts with age (11,30,80,82).

Burg (11) performed the most extensive study of aging and visual fields, testing approximately 17,300 people over an age range of 16-91 years. Targets of 46′ arc (7.5 footcandles) were presented at various positions separated by 5°, along a horizontal meridian in either temporal or nasal fields. The total visual fields (sum of both temporal fields) decreased progressively with age. From age 16 to age 50, the mean horizontal cross-section of the visual field declined by only 5° (from 175 to 170); after age 50, the decline in the mean visual field size accelerated significantly.

Several comments are in order here. First, more studies should be done with systematic variation of size, luminance, wavelength, contrast, and temporal characteristics of the stimulus. All these variables affect both the specification of field boundaries and the relative sensitivity of the periphery and fovea (77). Second, as Weale suggests (80), in healthy eyes age differences in sensitivity across the field most likely result from decreased retinal illuminance caused by senile miosis and reduced transparency of the ocular media.

Whatever the accuracy of Weale's interpretation, the fact is that, functionally, fields do diminish with age. As a result, under operational conditions (unless steps are taken to compensate for reduced retinal illuminance) the extent of the visual field is likely to be somewhat smaller for older observers.

Depth Perception

Depth judgment is a fundamental component of many visual tasks required in flying. These tasks include perceiving range, rate of closure, relative depth, and relative motion in depth.

Two types of cues give information about depth: binocular and monocular cues. Stereopsis, the depth response to retinal disparity, appears to decline in the general population from about age 40 (4). Considering the parallel age of onset, it is highly likely that this loss is due to age changes in the anterior part of the eye, including loss of accommodative convergence, and to decreased acuity. For example, using subjects who were screened for acuity of 20/20 or better and no ocular pathology, Hofstetter and Bertsch (33) found no changes in stereopsis with age. Thus, older Navy pilots with good acuity who are free of ocular pathology probably have undiminished stereopsis. Size constancy (the scaling of retinal image size against perceived distance to produce an accurate judgment of object size) does not seem impaired in old age (46).

Perception of position in depth in most military aviation tasks probably depends little on binocular convergence or classical stereopsis because of the short effective range of these two sources of information. In fact, under some conditions, monocular cues to depth may be adequate for many flying tasks. For example, under daylight flight conditions, landing performance is as good for pilots who are monocular and who are experienced with monocular flight as it is for experienced binocular pilots (29). However, there are several flight situations in which binocularity may be important, such as low-level rotary-wing aircraft operations, midair refueling, and vertical takeoff/landing aircraft operations. Regan and coworkers (63) have reviewed evidence suggesting that there are stereo mechanisms for processing motion in depth that, in contrast to classical stereopsis mechanisms, do not depend on viewing distance. Unfortunately, nothing is known about how these mechanisms for processing motion might change with age.

Depth information used in most flying maneuvers is probably derived primarily from geometric relationships in the visual environment. There are, however, no general methods of evaluating an individual's monocular depth perception. We assume that experience contributes greatly to effective judgment of depth, particularly in familiar environments. Thus, the effects of age and experience on depth perception may be confounded.

Temporal Resolution

There appears to be a loss with age in the temporal resolving power of the visual system. Temporally contiguous visual events that would be seen as separate by younger observers are frequently reported as fused or "smeared" by older observers (42,43,45,78). These observations are consistent with a hypothesis of increased persistence of stimuli in the older nervous system. For example, professional pilots over 40 years of age take longer than those under 40 to recover from the effects of an intense flash (7). Slowed ability to recover from rapid changes in illumination, such as may occur in moving between a lighted and a dark sky at dawn or dusk, could be a disadvantage to the older pilot.

Sekuler and coworkers (68) measured contrast thresholds with temporally modulated gratings of low spatial frequency (1 cycle/degree). Two groups, one with mean age 18.5, the other with mean age 74, were tested at two rates of grating drift, 0.5 and 10.0°/s. To see the moving grating, older observers needed slightly more than twice as much contrast as younger observers. The effect of age was slightly more pronounced at the higher rate of drift.

Considered with the above-mentioned losses in dynamic acuity and contrast sensitivity to low spatial frequency targets with age, this loss with age in the temporal tracking power of the visual system suggests differential loss in the "transient," as opposed to the "sustained," channels of the visual system (44). If such losses were also characteristic of older Navy pilots, they might encounter particular difficulty in detecting movement, certain forms of flicker, low spatial frequency targets, and in handling rapidly occurring sequential visual events.

Processing Visual Information

The operation of complex systems, such as high-performance aircraft, demands effective and rapid processing of visual and other information as well as the integration of information from various sources. Military aviation requires not only safe flying but also high levels of performance; for example, when many planes are waiting to land on an aircraft carrier, the slow or overly cautious pilot may endanger the lives of others. Military aircraft contain devices that can display changes in environmental variables at rates that can exceed the processing abilities of even the most attentive human observer. Designers of aircraft instrumentation system attempt to design systems in which the dynamic display of critical information is within the processing capacities of pilots. However, conditions that permit efficient performance by a 25-year-old naval aviator may not be adequate for his 45-55-year-old counterpart, for it has become increasingly clear that information processing capacities decline in this age range in the general population. Changes in the speed of information processing and resistance to distracting stimuli are especially important.

Speed of Processing—One of the most pronounced age differences in visual processing is a decline in speed. The clearest demonstrations of this decline are studies examining age differences in backward visual masking. In backward masking, the visual effectiveness of a target stimulus is reduced when it is closely followed by a masking stimulus. The asynchrony between the two stimuli at which the observer "escapes" the influence of such masking can be used to estimate the time required to process the target stimulus. Studies using healthy nonpilot subjects have consistently shown that this interval increases in older persons, indicating reduced speed of visual processing. These studies also indicate that this slowing occurs at both peripheral and central levels of the visual system (41,78). It is likely that this age-related slowing in visual processing is less pronounced in pilots; Szafran's studies (74,75) of older pilots indicate little age impairment in information handling capacity, except under the most taxing conditions. However, it may be under just such demanding circumstances that age-related loss in information handling capacity would be most critical for military pilots as well as for commercial pilots in emergency situations.

Resistance to Distracting Stimuli—The skilled pilot must extract task-relevant information from the environment in which that information is embedded. There is evidence of some impairment with age in this ability; for example, Glanzer and Glaser (26) asked Air National Guard officers and commercial pilots to identify partially obscured relevant shapes (e.g., plane, control tower) and "nonsense" geometric shapes. A significant inverse relationship was found between age and identification even in this healthy, relatively young group. There is also some evidence that the ability to attend selectively to relevant stimuli in the presence of distracting stimuli is involved in such real-life situations as flying proficiency and automobile accident avoidance (37,55).

Perceptual Organization

Perception of Incomplete or Degraded Stimuli—Older observers tend to have more difficulty perceiving ambiguous or incomplete targets, especially when these are presented under degraded viewing conditions. For example, Crook and his coworkers (14) examined the effects of exposure duration, luminance, contrast, and visual noise on the ability to identify objects. So long as viewing conditions were optimum and exposure durations long, age seemed to have no effect on target perception; however, as viewing conditions became more demanding, age did seem to diminish target perception. In this study the oldest observers were in their late 50s. It appears that older observers make less efficient use of partial information (16).

Perceptual Flexibility—Several studies suggest that older persons may be less likely to modify a perception once it has been established; for example, they report fewer "oscillations" of reversible figures and are less likely to report alternate percepts in ambiguous figures. These changes may be due to a decrease in the "perceptual span" of older persons or to increased cautiousness (34).

It is not known how reduced perceptual flexibility and inability to perceive incomplete stimuli would affect flying performance, although these reductions seem likely to have some impact. Military pilots must sometimes make fast decisions about the nature of a target that can be seen only imperfectly and they must quickly update their evaluations as better visual information is received.

CURRENT VISUAL STANDARDS

Pilots' vision is tested periodically as part of routine physical examinations. Although there are differences among the vision examinations given in the three military services and those required of commercial pilots by the Federal Aviation Administration, they are all basically similar in being designed primarily to detect pathology and oculomotor dysfunction, and to measure refractive status. This is illustrated by the vision portion of the Navy's physical examination (see Chapter 15, Manual of the Medical Department, U.S. Navy). Visual acuity is tested at distance (20 feet) and near, using either the Armed Forces Vision Tester (AFVT) or a suitable substitute. Depth perception, color vision, oculomotor balance (phorias), accommodation, and intraocular tension are measured. Field of vision is tested using moving fingers as test objects. A medical history is taken and the findings of ophthalmological and external examinations are noted. In order to pass the examination, pilots must be free of significant pathology and exhibit normal ranges of depth perception, color vision, oculomotor balance, and field of vision. Minimum acceptable levels of distance acuity and accommodation are specified as well as maximum acceptable astigmatism.

The physical examination screens for pathology, oculomotor dysfunction, and refractive changes that may occur as pilots age, but it cannot detect all age changes in visual function that may impair flying performance. Flight conditions can vary dramatically from the conditions of standard vision examinations. Acuity, for instance, is measured at illumination and contrast levels designed to maximize the subject's ability to discriminate; however, pilots often fly under scotopic conditions and sometimes also encounter extremely high levels of light intensity and glare. Age particularly affects visual acuity under extreme conditions of light intensity and contrast. There may be older pilots whose acuity drops more than normal under these extreme conditions even though it is within acceptable limits on a standard examination. Similarly, standard clinical measurement of visual field may not reveal problems that may show up under operational conditions. Under physical or emotional stress the visual field constricts (47). However, it is not known how much the degree of constriction varies among individuals and how it is affected by age or by repeated exposure to stressors.

The standard vision examinations fail to measure a number of visual functions likely to be important in flying performance and known to deteriorate significantly with age, such as dynamic acuity and speed of information processing. Contemporary views of visual information processing treat the physiological and refractive status of the eye as just one limiting factor in visual performance. Obviously, if an aviator's eye is not capable of transferring the information required for some task, that task cannot be performed. But even if the eye's response to visual stimulation is adequate, more central processes may limit the ability of the aviator to make use of that information. Effects of age on these central processes may be at least as important to flying performance as changes in the refractive status of the eye. The functions measured in the vision examination are necessary to evaluate an aviator's capability but are not sufficient in themselves to allow good predictions of the aviator's performance.

There are few data on changes in visual function specifically in military aviators and, as discussed in the following section, it is not clear whether data obtained from general populations are applicable to them. It would be useful if the routine vision examinations given all pilots could be used to supply some of the needed data; unfortunately, current recording techniques would make this difficult, if not impossible. For instance, if 20/20 acuity is required for maintaining flight status, the examiner may not record whether the tested pilot has vision better than 20/20 and, if so, how much better.

METHODOLOGICAL ISSUES

Several major methodological problems make it difficult to determine the effects of age on visual function and performance of tasks requiring vision.

General Problems in Research (73)

Cross-Sectional Studies—Most aging studies are cross-sectional in design: measurements of function are made over a relatively short period of time on individuals of different ages. In cross-sectional studies, it is not possible to separate clearly the effects of aging from those attributable to being born at and living through different periods in history, i.e. the cohort effect. Differences in experience, education, health, and so on are thus confounded with age; the impact of these factors must also be considered in attempting to understand the effects of aging on vision. It is important to recognize that the cohort effect would also occur in any cross-sectional studies using Navy pilots; subjects of different ages are also likely to differ on a variety of other factors as well.

Longitudinal Aging Studies—Longitudinal studies avoid confounding age and cohort by following the same individuals through time, thus providing true individual trends. However, longitudinal designs also have significant limitations: they take a long time to carry out, they are expensive, and they often suffer from selective drop-off of subjects, decreasing the sample size and making it less representative of the original group. Since culture, technology, and measurement procedures change over time, it is difficult to separate aging from "time of measurement" effects. Obviously, these same limitations apply to any longitudinal study of pilots (52).

Extrapolating Data

The working group is not aware of any completed comprehensive studies that relate age to the visual function of Navy or other military pilots. It is difficult to extrapolate findings on age effects to a population not sampled. In several important respects outlined below, Navy pilots are not typical of the larger population.

1) There may be some group differences in health, health care, nutrition, education, exposure, stress, etc. that must be taken into account. Since visual functioning depends on the health of many organ systems, groups having better health may run less risk of visual dysfunction.

2) Navy pilots may be subject to different biases in their attitude toward doing well on vision examinations. Their careers and perhaps their self-esteem depend on passing vision examinations. Personnel conducting examinations may be reluctant to disqualify pilots from flight status, particularly for marginal failures to pass standard vision requirements.

3) Navy pilots continuously practice their flying skills; the effects of continual practice on the "normal" rate

of deterioration with age in visual function and information processing skills is not known. Conceivably, practice may retard deterioration in pilots' skills.

These three differences between Navy pilots and the general population limit the usefulness of extrapolations from studies of aging in the general population. They also reinforce the importance of a more direct approach: direct studies of military pilots would be much more useful than studies of the general population.

Variability of Performance

The variability in visual function among and within individuals raises a related problem. The variability in virtually all visual functions is considerable at any age. For example, the contrast sensitivity of normal healthy observers in a given age group varies by at least 2.5-1 (21,24). Large individual differences also occur in the functions assessed by routine eye examinations. Even more to the point, variability in performance appears to increase with age for virtually all tasks

Suppose, for example, that someone wished to estimate how many pilots would be likely to fall short of the Navy requirement of a minimum of 2.5 diopters accommodative amplitude for retention in Service Group I. On the basis of general population studies (32), one would expect less than 50% of pilots age 45 to fail.

Function and Performance

Even though we have some general understanding of the changes in visual function occurring with age, we can say very little about the effects of visual deterioration on performance of complex tasks, such as flying. With a few important exceptions, there has been little experimental study of such effects, even though they presumably occur and may be of considerable consequence. Similarly, we can say little with certainty about the general problem of how much of the variance in complex task performance among individuals can be accounted for by differences in measurable visual functions (38).

Accident rates might give an indication of whether deteriorating biological functions influence pilots' performance as they get older. Data has been collected on the incidence of aircraft accidents and incidents as a function of pilots' age (35). Incidence among U.S. commercial air carriers declined with pilot age in the range 20-59. These data must be interpreted cautiously, however, because older pilots are likely to be assigned different flying routes and schedules because of their seniority. Among general aviation pilots with more than 2,000 h of flying time, pilots under age 30 have the highest accident rates, and there is no consistent trend in the 30-70 age range. Among all general aviation pilots, those in the 60-70 age range have higher accident rates. The general aviation data, however, do not include information on the amount of flying actually performed and thus are difficult to interpret for our purposes. In summary, accident occurrence data could help shed light on the issues raised in this report, but existing studies have not included critical information.

One current approach is exemplified by the test development program at the Naval Aerospace Medical Research Laboratory, Naval Air Station, Pensacola, FL. Acknowledging that flight performance is difficult to quantify and that flying performance includes many skills and abilities apart from visual ones, the program concentrates on mission segments that are critically dependent on vision. These segments include air-to-air target acquisition and carrier landings under both daytime and nighttime conditions. The goal is to develop a battery of tests that measure visual abilities that are important for these mission segments. Ultimately, the test battery will be validated against in-flight measures and the appropriate weights for various tests determined.

The data in this area are limited in part because measuring performance of complex tasks is extremely difficult as well as time-consuming and expensive. There is no single indicator, except perhaps expert opinion, of overall quality in the flying performance. Some individual components of performance (e.g. sink rate in landing approaches) can be measured, but these are limited, and it is not clear how representative they are of overall performance. Variation in individual performance is considerable and often depends on the specific task; thus, large number of subjects and careful experimental design are required. Nevertheless, considerable progress has been made in recent years in experimental measurement of performance at complex tasks, particularly in military systems, including aviation (61, particularly papers by Vveuls and Woolridge). Multiple regression techniques and computers have been used to assess the enormous amount of raw data generated.

Another fundamental difficulty occurs because complex tasks can often be accomplished by several different approaches. It is well known from ergonomics and human factors research that, in most instances, an operator can perform a complex task in a number of different ways. This general principle is also manifest in physiology: the redundancy of organization and the adaptability of the central nervous system may allow one to perform specific acts or functions even when the processes normally responsible for them have deteriorated. Thus, it is difficult to determine the relationship of measurable visual functions to complex task performance outside the laboratory because subjects may be able to use alternate perceptual and cognitive strategies to perform given tasks adequately, even though there has been some degradation of visual functions. Experience may play an important role in such compensation, and it is conceivable that senior pilots may learn alternate ways of information processing that allow them to perform some tasks as well or even better than younger pilots, despite deterioration of measurable visual function. For example, Szafran (75) found that, on both auditory and visual discrimination tasks, older pilots tended to employ strategies that offset the effects of age-related sensory loss.

Conditions of stress and information overload may affect the visual performance of pilots. These conditions correspond to emergency situations in which a pilot needs to function most effectively. Visual functions, however, are measured in the clinic and the laboratory singly, often under conditions chosen to optimize performance. Data obtained under these optimal conditions may give a misleading picture of the importance of age on visual task performance.

FINDINGS AND CONCLUSIONS

Most visual functions eventually show some deterioration with age. The working group's review of the literature reveals that a fair amount is known about changes that occur in various visual functions with age; the rate of change can be roughly characterized for the general population. Individual variation in the rate and extent of deterioration, however, is great, and for most functions we can make only rough qualitative predictions about the visual difficulties individuals encounter. Even for presbyopia, which is one of the best-described and most predictable of vision changes with age, there are considerable differences in rate of change among individuals.

The working group was confronted with a difficult task: assessing which age changes in vision are likely to be relevant to military pilots. Few experimental studies are directly relevant to this issue; the few data available do not allow quantitative characterization of given visual functions in complex tasks, such as flying aircraft. The working group identified several age-related changes in vision that are likely to be of considerable importance in flying performance. In making this assessment the group drew on what data exist as well as previous assessments; we emphasize, however, that the assessment involves opinion as much as fact. (57,61 discuss the roles of expert opinion).

Age Limitations on Vision

1. *Contrast Sensitivity.* Pilots, particularly in military aviation, must detect, analyze, and respond appropriately to visual objects of low contrast. It is now established that there is only a weak, though statistically significant, correlation between visual acuity measured under clinical testing conditions (i.e. with high contrast) and subjects' ability to detect targets with low contrast (58).

2. *Dynamic Acuity.* Pilots are required to respond to moving targets and other stimuli often presented only briefly and in rapid succession. However, static acuity is a poor predictor of the ability to detect moving targets (dynamic acuity), at least in young nonpilot subjects (12). Dynamic acuity appears to decline with age (62); however, this has not been examined in pilots.

3. *Recovery From Glare.* Military pilots sometimes encounter rapid and extreme changes in glare. Older people generally experience increased difficulty with glare because of light scattering in the ocular media and, possibly, slower rates of dark and light adaptation. Older pilots have been shown to take longer to recover from the effects of glare (7).

4. *Function Under Low Illumination.* Military pilots must at times perform visually demanding tasks under nighttime (scotopic) conditions. Performance under scotopic conditions may be correlated only weakly with performance under the photopic conditions in which vision is usually tested (25,71). Moreover, variability of performance is at least twice as great under scotopic conditions as it is under photopic conditions (39). Changes with age in the lens and pupil reduce the amount of light reaching the retina. Age-related changes in the retina itself may further reduce visual performance under conditions of low illuminance.

5. *Information Processing.* Research indicates that, as they age, healthy subjects from the general population experience a significant loss in the speed with which visual information can be processed (41,78). In older pilots, this decline appears to be noticeable only under demanding or overload conditions (74). There also seems to be a decline with age in the ability to selectively attend to one source of information in the presence of competing messages (13,16). The ability to attend selectively appears to be correlated with flight proficiency (37).

Supplementing Vision Tests

The vision examinations currently given to military and commercial pilots do not measure contrast sensitivity, dynamic visual acuity, recovery from glare, low illumination functions, or information processing capacities. Deterioration of any of these functions would probably go undetected, with potentially serious consequences, unless a pilot noticed problems with his or her visual performance and requested evaluation.

The working group suggests that it would be highly desirable to supplement current vision examinations for both military and civilian pilots—if feasible—with measures of these visual and information processing functions. Feasibility assessment should precede any attempt to implement supplementary tests, and both research and policy issues would have to be examined.

1. *Research Issues.* For some functions, such as dynamic visual acuity, existing methods of measurement could be brought into use fairly readily; for others, e.g. information processing capacity, considerable research and development would be required. For such functions, existing knowledge is insufficient to establish standards that could be used in deciding the flight status eligibility of pilots. To establish such standards in a rational way, data would be required on the distribution of performance values for visual functions among the populations of interest (pilots). Considerable research would also be required to establish the relative importance of given functions to flying performance. For some of these functions, instrumentation would have to be developed and standardized for routine screening, which could prove to be a major undertaking requiring considerable time and expense.

If this research were undertaken, it would also be desirable to address a related question: would early measurements of critical visual functions in an individual help to predict changes in that individual's vision in subsequent years? Given the present paucity of longitudinal data, one can only speculate on the answer to this question.

2. *Policy Issues.* Policy considerations go beyond the charge to this working group, but it is obvious that a number of issues would require close attention. For example, would new tests be sufficiently reliable to provide a basis for decisions about selecting student pilots and allowing qualified pilots to remain on flight status? The effects of employing new tests on the workload of examiners, the careers of individual pilots, and the pool of pilots available would also have to be considered. The potential benefits of developing supplementary measures, should this prove feasible, would include improved detection of deterioration in visual functions that are important in flying and the selection of pilot candidates with superior visual capabilities.

Research Needs

The working group is aware that it is not uncommon for groups faced with difficult issues to fall back on recommendations for more research. However, it is clear that the issues involved here are of considerable importance. The accumulated work on vision and perception in the past decade makes it more likely than ever before that such a research effort could now produce useful and concrete results. We know enough at the present time to design and execute studies that would yield useful answers to the difficult questions in this area. Better understanding of the relative importance of measurable visual functions to flying performance, as well as the impact of changes in these functions, would greatly benefit the military services and other agencies concerned with pilot performance.

1. *Visual Skills Important to Flying Performance* (61 discusses complex task measurement). There is clearly a strong need to be able to relate differences in visual skills to complex task performance much more precisely than is now possible. Obviously, this is a difficult undertaking, and it is unlikely that simple quantitative metrics can be developed; nevertheless, there is much that could be usefully done.

Six general measures could be particularly useful in assessing how differences in measurable visual functions affect flying performance:

(i) Performance of actual flight maneuvers, using selected criteria such as wave-off rate for carrier landings;

(ii) Performance of maneuvers in flight simulators with visual displays;

(iii) Performance of laboratory tasks analogous to some tasks of actual flight—for example, detection of aircraft silhouettes (23);

(iv) Aircraft accident data;

(v) Performance in competitive exercises, including simulated combat flying; and

(vi) Systematic performance evaluation by fleet squadrons.

Obviously, all of these experimental approaches raise questions of interpretation. For example, the selection of wave-off or bolter rates for carrier landings as a criterion is somewhat arbitrary and subjective. Also, it has not yet been determined how closely or under what circumstances performance in a simulator parallels performance in actual flight. Nevertheless, the working group feels that this kind of study could generate valuable data.

These six approaches could be employed both for population studies, in which regression analysis would evaluate the contribution of differences in measured visual functions to performance levels, and for studies of individuals, in which deterioration of visual function would be simulated. Obviously, each has advantages and limitations.

2. *Aging of Visual Functions in Navy Pilots.* Almost all the available information regarding aging and vision has been derived from populations of nonpilots. For reasons already noted, this complicates the task of offering solid recommendations for naval aviators. The effects of aging on military flying performance can be determined conclusively only by research with military pilots. Multivariate research approaches using longitudinal or other sequential designs would probably be most useful. It might also be possible to make some use of information obtained from routine vision examinations given to large numbers of military pilots over the course of their flying careers; however, this would require developing standardized data recording and collection techniques.

3. *Role of Experience and/or Compensation.* Research is needed to assess the degree to which older pilots can use their greater experience to compensate for loss in visual function. This research should also consider the extent to which such compensation can occur under critical overload conditions, the degree to which it can be augmented or made unnecessary by auxiliary equipment (e.g. lenses, illumination adjustment, special visual displays, etc.), and the extent to which pilots, especially older pilots, can be trained to develop and use such compensatory skills.

4. *Interaction Between Age and Other Factors Influencing Performance.* Relatively little is known about the direct and indirect impact of fatigue, emotional distress, illness, and other factors that may influence flight performance. Some of these influences may be chronic, others transient. Impairment of the circulatory system, for example, can affect the viability of the retina within a comparatively short time. Vascular changes of sufficient size and duration can thus lead to reduced visual function. There is a need to consider how age may interact with these factors to influence performance, especially under stressful conditions.

Appendix: Contrast Sensitivity Methods

One common source of confusion in discussions of contrast sensitivity is its connection with such traditional measures of vision as visual acuity. Most important, does the contrast sensitivity function (CSF) supply any information about someone's visual capabilities that acuity does not? The following discussion attempts to answer such questions.

The importance of the CSF may become clearer if we adopt the following classification. Consider three classes of tasks and viewing conditions, differing in how much each requires an observer to see either fine details (i.e. high spatial frequencies) or gross features (i.e. lower and intermediate spatial frequencies). In the following explanation, "ideal viewing conditions" refers to photopic levels and clear visibility; "less favorable viewing conditions" include mesopic (twilight) or scotopic (night) luminance levels, disability glare, and/or fog and precipitation.

Class I tasks are those for which the ability to see fine details is indispensable. Ability to perform such tasks is limited by the observer's visual acuity. Such tasks include threading a needle, retouching a photograph, and reading fine print.

Class II tasks are those that, under ideal viewing conditions, make use of the ability to see fine detail but that, under less favorable viewing conditions, can be performed adequately using coarser features of the objects and targets.

Class III tasks are ones for which, regardless of viewing conditions, fine details are unimportant. Such tasks include various forms of figure-ground discrimination (48), recognizing faces at "social" viewing distances (58), and some functions required in automobile driving (49).

Under unfavorable viewing conditions, e.g. deep twilight or fog, no matter how good photopic acuity is, one cannot see fine details (high spatial frequencies). As a result, Class II tasks that can be performed using fine details in clear daylight require the observer to use the target's intermediate or lower spatial frequencies when performed at twilight. For example, detecting distant aircraft in daylight and good weather probably depends on the high spatial frequency content of the retinal image. In such conditions, acuity would determine the slant range at which detection occurred. But in deep twilight or fog, regardless of an observer's acuity, fine details are invisible. The slant range at which aircraft are detected decreases and, at the moment of detection, the aircraft may subtend visual angles many times the eye's resolution limit. Under these conditions, detection hinges not on an observer's acuity but on the sensitivity to lower or intermediate spatial frequency content of the retinal image.

This classification scheme would be of no practical use if a person with high acuity necessarily had high sensitivity over the entire range of spatial structures that was needed to see, or, conversely, if a person with poor acuity would necessarily have low sensitivity over that same range. In that event, we could reasonably measure only visual acuity, since all sensitivity would be predictable from that single measure.

But acuity is not correlated with sensitivity to all spatial structures that may be important for visual performance. Tests with large samples of observers reveal that sensitivity to high spatial frequencies does not predict a person's sensitivity to intermediate or low spatial frequencies (23,24,67). As a result, knowing a person's ability to see an acuity target or other objects with spatial structure near his or her resolution limit will not help predict the visibility of the same target under scotopic or mesopic conditions (25). In fact, the relative independence of an observer's sensitivity to low spatial frequencies from sensitivity to high spatial frequencies explains the near-zero correlation between visual acuity measured under photopic and scotopic conditions (39,40). Under scotopic conditions, fine details are invisible, forcing the observer "up the eye chart," where letter or target recognition no longer depends on sensitivity to high spatial frequencies.

In summary, to assess potential performance in all task/weather combinations, one needs to measure a variety of relatively independent visual skills. The CSF provides one set of such measures.

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This report reviews what is known about the effects of age on visual function and discusses the implications of age-related changes in vision for the flying performance of military pilots. Most visual functions decline to some degree with age, and the rate of decline has been roughly characterized in the general population. There is, however, virtually no data on military pilots, and extrapolation from the general population requires caution. Individual variation in the effects of age is great, and military pilots are

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a select group presumably in better general health than the general population. Several visual functions that decline with age seem particularly relevant to pilot performance: contrast sensitivity, dynamic acuity, recovery from glare, function under low illumination, and information processing. Vision examinations currently given to military and commercial pilots do not measure these visual functions. The feasibility of supplementing existing vision examinations with measurements of these functions should be explored; such an assessment should consider both research issues and policy implications. Research is needed on several major problems in this area. It is not possible at present to characterize well the effect of changes in visual function on the performance of complex tasks, such as flying. This report suggests several specific measures that might help characterize the effects of changes in visual function on pilot performance. Data on changes in visual functions with age should be collected from military pilots, preferably with multivariate, longitudinally designed studies. Research is suggested to assess the extent to which experienced pilots may compensate for declining visual functions and to determine how such compensation is achieved. The report suggests studies of the interaction of age with other factors, such as cardiovascular changes, that may affect performance, especially under stress.